U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS—BULLETIN No. 28.
MILTON WHITNEY, Chief.

STUDIES ON THE PROPERTIES OF AN UNPRODUCTIVE SOIL.

BY

BURTON EDWARD LIVINGSTON, J. C. BRITTON,
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BUREAU OF SOILS.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., May 24, 1905.

Sir: I respectfully transmit herewith a technical paper entitled "Studies on the Properties of an Unproductive Soil," which I recommend be published as Bulletin No. 28 of the Bureau of Soils.

Respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

PREFACE.

It is more than three-quarters of a century since the problem of the fertility of the soil and its conservation and control, as, for instance, by manurial or fertilizer applications, was recognized as a chemical problem. Later it has come to be recognized that the physicist, the bacteriologist, and nowadays also the physiologist, must lend assistance in studying the factors involved in this great problem.

Hitherto the problem has been attacked mainly from the analytical point of view. Analyses of the ashes of plants have shown that a certain few mineral substances are always present in the plants and are essential to them as nutrients. This theory has been amply confirmed by water and sand cultures. Obviously these mineral nutrients are derived from the soil, but the amount or proportions in which they may be present in the plant have not generally been found to bear any definite relation to the size of the crop, the fertility of the soil, nor its manurial requirements. The percentage of ash in poor crops is frequently larger than in good ones, and often a poor crop removes absolutely larger amounts of mineral matter from the soil than does a good crop of the same species or variety.

With the recognition of the fact that plants obtain their necessary mineral nutrients from the soil came the conception of "available" plant food or food constituents—that is to say, that of the total amount of mineral nutrients which the soil might contain only a portion could be obtained from it by a crop or a succession of crops. This idea, while fruitful in leading to much work, has, however, had an academic rather than a practical value. It has been the guiding principle in the major part of the chemical work that has been done upon soils, as well as in the vast number of pot, plot, and field experiments that have undeniably led to some valuable information concerning soils. It has failed, however, in leading to any reliable general method for estimating or determining the fertility of a soil or its fertilizer requirements.

The chemical analysis of a soil has hitherto consisted in the extraction of a sample, under some standard conditions of time and temperature, with an aqueous solution of some electrolyte or electrolytes, usually an acid, and the estimation of the mineral constituents

brought into solution. All these extraction methods, without exception, are purely empirical. Two methods of control have been employed. In the first it has been attempted to select such a concentration of extracting solution as would take from the soil the same amounts, or some factor of the amounts, of mineral constituents as an ash analysis would show that a crop would remove from the soil. This has proved vain, however, since different crops, and even the same crop under slightly varying conditions, remove not only different amounts, but widely different proportions, of mineral constituents from the soil. In the second method of control, the results of the analyses are compared with the results obtained from a soil or soils of known fertility, as determined by pot, plot, or field cultures or as a matter of general farm experience. This method has not been found satisfactory. For instance, the writer has recently had occasion to investigate two soils in northern Ohio whose crop history has been carefully followed for upward of a decade. One of these soils yields, on extraction with concentrated hydrochloric acid, more potassium but less phosphoric acid than does the other, yet the first soil responds much more than does the second to the addition of potash fertilizers, while the second soil gives a decidedly better response to phosphatic fertilizers than does the first. Numerous instances of the kind can be readily found in the voluminous mass of analytical data now available.

Seldom, if ever, do samples which give results in fair agreement with one another when treated with one solvent show the same order of agreement when another solvent is used. A solvent which appears to yield satisfactory results with one set of soils generally fails when used with another set. Yet there is no field of scientific inquiry in which there has been more activity, and scarcely a month passes that does not see some new solvent or some new modification or manipulation of an old solvent seriously proposed for the analytical examination of soils, so that there now exists a bewildering array of methods vouched for by recognized authorities. This Bureau has itself carefully investigated one method—the extraction from the soil, upon which a crop was growing, by water, under standard conditions, at more or less regular intervals throughout the growing season—with the result that, in general, no correlation could be made between the amounts of mineral substances found in the aqueous extracts and the actual yield of crops observed.

One important purpose which it was hoped to achieve by these various methods of analyzing the soil is the determination of the fertilizer requirements. In general, however, the amounts of the several mineral fertilizers which experience has shown to be necessary to produce marked, or even maximum, differences in crop yield

are far too small to appear in the results of the chemical analysis of the soil as it is usually made. Moreover, the assumption that the fertility of a soil, or its crop-producing power, is dependent only, or even mainly, upon the mineral constituents which it may contain is seldom justifiable. It is certain that in many cases the character of the organic matter which the soil may contain has relatively the most importance in determining its crop-producing power. In others, the bacterial and similar conditions are probably the controlling ones. In fact, it now seems probable that in but very few cases is there an actual lack of mineral nutrients, and the mineral substances from which they are derived are sufficiently soluble to be readily available and to maintain the soil moisture at a suitable concentration for a nutrient medium.

It would seem that the time has come when progress can be better made by attacking the problem of the soil in its relation to crop production from the synthetical rather than the analytical point of view, and it is along such lines that much of the work of this Bureau has been directed in recent years. The application of modern chemical views respecting solution phenomena, adsorption phenomena, colloids, enzymes, etc., to soil studies has demonstrated their great importance in determining crop production, and no less helpful perhaps are our present concepts concerning the biological processes taking place in both the soil and the plant. Until these various classes of phenomena have been more thoroughly and systematically studied, no basis for a rational fertilizer practice can be obtained. The authors of the present paper have had a leading part in the development of the work which the Bureau has been conducting along these newer lines of soil investigation, and it is believed that this description of the investigations which have made possible the production of a luxuriant lawn upon a naturally unproductive soil at Takoma Park, Md., as well as helped in a very large measure in the development of our present views concerning soil fertility, will mark a decided step forward in soil studies and prove suggestive to other investigators in this most important branch of applied science.

Frank K. Cameron.

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STUDIES ON THE PROPERTIES OF AN UNPRODUCTIVE SOIL.

INTRODUCTION.

For many months an investigation of the physiological properties of one of our most unproductive soils has been in progress in these laboratories. The extreme unproductiveness of this soil, together with the facts that its physical nature is not unfavorable to plant growth and that its water extract exhibits nutrient salts in quantities as great as or greater than those found in the extracts of other soils which are agriculturally fertile, rendered these studies very promising of important results, not only with regard to this particular soil and its practical treatment, but with regard to the general theory of soil fertility as well. It seems that the promise has been, in part at least, fulfilled, and the results of the work are here presented.

THE PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL.

The soil in question is found at Takoma Park, Md. It occurs in a small area devoted to residences and was notable at first from the futility of repeated attempts to make a lawn upon it. It has been termed Takoma lawn soil. It is a brownish-yellow coarse sandy loam, 3 feet or more in depth, resting upon material similar to the Susquehanna clay. Samples taken at intervals from the surface downward show a gradually increasing proportion of silt and clay.

Two mechanical analyses of different samples of this soil, made in the laboratories of this Bureau at different times, are given below. They show the percentage amounts of the various-sized particles in the usual manner.

TABLE I.—*Mechanical analyses of Takoma lawn soil.*

Conventional names.	Diameter of particles.	Sample 1.	Sample 2.
	mm.	*Per cent.*	*Per cent.*
Fine gravel	2.0 -1.0	4.1	2.5
Coarse sand	1.0 - .5	28.4	32.5
Medium sand	.5 - .25	10.8	12.1
Fine sand	.25 - .10	8.2	8.0
Very fine sand	.10 - .05	2.7	2.3
Silt	.05 - .005	29.2	26.9
Clay	.005-0	16.5	15.5

The soil is rather peculiar in that it possesses relatively large amounts of coarse and of fine material, but only small quantities of medium-sized particles. It belongs in the group of ill-defined soils designated as Susquehanna clay loam, as described in the Soil Survey of Prince George County, Md.,[a] although it is markedly more sandy than the typical samples of that soil.

Chemical analyses of Takoma lawn soil have been made in these laboratories from time to time. The amounts present of those substances which are most important in plant growth are shown in the tables below. Table II gives the amounts of water-soluble matter obtained in the aqueous extract of the soil by the method described in Bulletin No. 22 of this Bureau. Table III gives the results of an acid digestion.

TABLE II.—*Analysis of water extract of Takoma soil in parts per million of air-dry soil.*

Calcium (Ca)	11.7
Potassium (K)	22.7
Phosphate (PO_4)	7.6
Nitrate (NO_3)	5.5

TABLE III.—*Chemical analysis by acid digestion (HCl, Sp. gr; 1.115) of Takoma soil, results stated in per cent by weight of air-dry soil.*

Constituent.	Per cent.
Potash (K_2O)	0.135
Lime (CaO)	.145
Phosphoric acid (P_2O_5)	.11
Sulphuric acid (SO_3)	.05

The soil itself and its aqueous extract are acid in their reaction toward litmus, the extract is acid toward phenolphthalein, but not toward methyl orange. This would seem to indicate that the acidity is due to acid phosphate or to some organic acid, more probably to the latter.

The amount of organic matter present is 3 per cent, which seems to be extremely large for such a light-colored soil as this. This material must be in some light-colored form, quite different from the dark humus usually occurring in the upper layers of soils. The total nitrogen present was found to be 0.1 per cent.

THE PHYSIOLOGICAL PROPERTIES OF THE SOIL.

Although the Takoma soil contains, as has just been shown, quite large amounts of finely divided material, thus exhibiting a relatively

[a] Bonsteel, Jay A., and party. Soil Survey of Prince George County, Md., Report of Field Operations, Bureau of Soils, U. S. Dept. of Agr., 1901, p. 202.

high water-retaining power, and although it lies in a region not subject to extreme drought, yet the natural vegetation covering it is quite distinctively of the zerophilous type. The native plants are for the most part those forms which are structurally and physiologically adapted to a dry habitat. The trees are pine, several oaks, and chestnut; the undergrowth is very sparse, comprising huckleberry, mountain laurel, *Antennaria plantaginifolia*, and several xerophilous grasses. The surface of the soil is largely free from vegetation or occupied only by patches of moss (especially Ceratodon) and lichens.

Certain cultivated plants, when growing on the Takoma soil, show marked stunting, both of roots and of tops. White and red clover (*Trifolium repens* and *T. pratense*) produce tops dwarfed to an extreme degree; the leaves are small and the stems are extraordinarily woody. The roots penetrate only a few centimeters and are manifestly inadequate for furnishing water to plants of normal size. Grasses show the same dwarfing. Wheat seedlings when grown in this soil, held in wire baskets of the form described in Bulletin No. 23 of this Bureau,[a] show also the same dwarfing. The stems and leaves are short; the former are slender and the latter narrow. The primary roots fail to develop to normal length and exhibit an increase in diameter, often having swollen regions, especially at the tips. Root branches are almost entirely absent even at the end of three weeks' growth, and the few existing ones are extremely short, a condition never found in similar cultures of the same plant in more fertile soils.[b] It seems very probable that the character of the soil is effective directly upon the roots, inhibiting normal branch growth and even causing stunting and swelling of the primary roots. The character of leaves grown on this soil is, as far as can be determined, the same as that of normal leaves from a fertile soil. There is no difference observable excepting the difference in size already mentioned, and transpiration per unit of leaf surface is the same.[c]

If actual paucity of water in the soil could be considered as possibly the effective factor in the stunting of the clover plants described above, and in excluding from the natural vegetation other plants than those adapted to dry soil, this position becomes absolutely untenable in regard to these cultures of wheat. For, at the beginning

[a] Bul. 23, Investigations in Soil Fertility, Bureau of Soils, U. S. Dept. Agr., 1904, p. 38.

[b] The condition of wheat roots in this soil is described with figures in a paper by one of the authors to appear in the Botanical Gazette for the current year: Livingston, B. E., (1) Growth of Roots and Tops in Wheat, Bot. Gaz., 1905.

[c] Data in connection with this statement are presented in a paper which is to appear in the Botanical Gazette for 1905: Livingston, B. E., (2) Relation of Transpiration to Growth in Wheat.

of an experiment, the soil of the baskets was made up to its optimum water content, from 14 to 17 per cent by weight of oven-dry soil, and the water content was kept approximately uniform throughout the experiment by the addition, every few days, of the amount lost by transpiration. Thus it became certain from the very start that the natural xerophytic nature of this soil is not due to actual lack of water. The chemical analyses show far too small amounts of soluble material to warrant the supposition that these may be effective through physical concentration. Osmotic pressure of the soil solution is thus ruled out of the question here, as it was in the case of bog waters by the freezing point determinations of one of the authors.[a]

INVESTIGATION OF PHYSIOLOGICAL PROPERTIES.

METHOD.

To determine if possible something in regard to the properties of Takoma soil which are active in producing the dwarfing of wheat plants just described, a large number of basket cultures have been grown with variously treated soil. The soil was mixed by hand with sufficient water to bring it to what has been found by experiment to be the optimum for growth in this soil. At what point this optimum was attained could be determined quite readily by pressing the moist soil between the fingers, it having been found that soils so prepared did not vary in water content beyond a range of 3 per cent, even when samples are made by different persons. With the optimum here used the soil contained, as stated above, between 14 and 17 per cent of water, computed on the weight of oven-dry soil. It has been shown by experiment that slight variations in the water content of this soil have no appreciable effect upon the growth of wheat; baskets ranging in water content from 10 to 20 per cent gave equal growths.

Soaked seeds of the Russian "Chul" wheat, grown in Arizona, were planted in the paraffined wire baskets of moist soil and allowed to grow till the shoots had attained a height of from 2 to 4 centimeters. The baskets were then sealed at the top with paper and paraffin, and weighings were taken at intervals of two or three days, the loss by transpiration being made up by adding the necessary amount of water after each weighing. The cultures were usually carried on with five duplicate baskets of each soil treatment. Six seedlings were grown in a basket, thus giving 30 seedlings for each test. The plants were grown in a greenhouse, where the different

[a] Livingston, B. E., (3) Physical properties of bog water. Bot. Gaz., **37**: 383–385, 1904.

cultures always stood side by side so as to give as uniform conditions as possible.

At the end of each experiment, after a growth of two or three weeks, the partial transpirations were added for the total transpiration, which has been found to be practically a measure of the growth of the plants[a] in different treatments of this soil. In some cases also the green and dry weights of the subaerial portions of the plants were determined.

IMPROVEMENT OF THE SOIL.

It has been found that the unproductiveness of the soil under investigation can be entirely corrected by relatively large amounts of fermented stable manure or green manure, and, to a great extent, by several other substances. Manure which had been thoroughly fermented by lying in a pile for several weeks, during which time it had been turned over a number of times, was thoroughly mixed into the soil from which pot cultures were to be made. Cultures of this kind are described, figured, and discussed in the papers already referred to on the relation of transpiration to growth and on the growth of roots and tops.[b] The soils to which manure was added in amounts of from 5,000 to 50,000 parts per million by weight of dry soil show very marked beneficial effects, which are roughly proportional to the amount of manure added.

In the manured soil the tops are large and vigorous, giving high figures for transpiration as well as for green weight, while the roots branch profusely and exhibit phenomenal growth. A single example from a number of experiments will show the relation of growth in the natural soil to that in the manured. This is the series of cultures numbered II in the paper on transpiration above cited. It ran for eighteen days. In Table IV are given the data bearing on the present discussion. The percentage increase in transpiration and green weight is calculated upon the basis of these quantities for the untreated soil, considering them as unity.

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[a] See the paper already cited, Livingston, B. E., (2).

[b] Livingston, B. E., loc cit., (1) and (2).

TABLE IV.—*Total transpiration and green weight, in grams, of wheat plants in Takoma soil, and the same with manure treatment.*

Treatment.	Total transpiration.	Green weight of tops.	Increase.	
			In transpiration.	In green weight.
	Grams.	*Grams.*	*Per cent.*	*Per cent.*
Takoma soil untreated	30.4	0.65		
Same + 5,000 p. p. m.[a] manure	30.6	.71	0.06	9
Same + 10,000 p. p. m. manure	55.6	1.30	83.0	100
Same + 20,000 p. p. m. manure	88.6	1.91	191.0	194
Same + 30,000 p. p. m. manure	91.5	2.22	201.0	242
Same + 40,000 p. p. m. manure	99.2	2.46	226.0	278
Same + 50,000 p. p. m. manure	105.2	2.59	246.0	298

[a] The abbreviation "p. p. m." is used to denote parts per million by air-dry weight of soil.

Green manure, in the form of the stems and leaves of the cowpea, grown in the greenhouse for the purpose, shows still more marked effect upon this soil. The stems and leaves were ground in the green condition and a sample was weighed, dried, and reweighed, and its original moisture content determined. This fresh-ground material was mixed into the soil in the proportion of 9,000 parts of dry plant matter per million of air-dry soil. The effect of this green manure is shown in an experiment the results of which are presented in Table V. In this experiment five baskets were prepared with treated Takoma soil and the plants grown in these were compared with those in the untreated. At the end of the period of these cultures, the treated soil was removed from the baskets, separated from the old roots, returned to the baskets and replanted, a control in fresh untreated soil being again grown for comparison. In this manner four successive crops were grown on the same sample of treated soil, each crop being compared with that from a fresh untreated sample of the same soil.

TABLE V.—*Percentage variations in total transpiration, green weight, and dry weight of 30 wheat plants in successive plantings in Takoma soil plus 9,000 parts per million of green manure, compared with a control in fresh untreated soil.*

Duration of culture.	Percentage variation from culture in fresh untreated soil, considered as unity.		
	Total transpiration.	Green weight.	Dry weight
	Per cent.	*Per cent.*	*Per cent.*
December 21, 1904, to January 18, 1905	71	130	71
January 19, 1905, to February 10, 1905	371	460	257
February 15, 1905, to March 11, 1905	131	118	61
March 15, 1905, to April 7, 1905	11	−3	

A very marked increase in the growth of the plants as the result of the use of green manure is evident, but with successive plantings this increase diminishes, until in the last planting it has practically disappeared. The green weight is 3 per cent lower here than in the fresh control. The low percentage increase for the first planting is probably due to some depressing substances in the fresh green manure—substances which become harmless as the manure decays.

It was also found that leaves of such plants as oak, chestnut, sumac, etc., increase the productiveness of this soil very markedly. The green leaves were gathered, ground, mixed into the soil, and allowed to decay there, after which treatment the fertility was tested by the basket method. By far the most active leaf in increasing the productiveness of this soil is that of the sumac (*Rhus glabra*).

All the varieties of leaves used contain, of course, considerable amounts of mineral salts, but in considering the nature of sumac leaves as compared with that of the others it was immediately suggested that the beneficial substance with which we had to deal here might be tannic acid, since sumac leaves contain a very large percentage of this substance. A number of tests were therefore carried out to determine whether tannic acid itself might be beneficial upon Takoma soil. In one of these experiments, which ran from October 25 to November 25, 1904, a soil which had been treated with 1 part per million of this acid supported plants which gave an increase in transpiration above that of a culture in the untreated soil of 79 per cent. More tannic acid was injurious to the plants and less was not as beneficial; this concentration appears to be the optimum. Another similar experiment, which ran from October 12 to November 2, 1904, gave an increase in transpiration of the treated over the untreated soil of 66 per cent. Other experiments gave similar results.

In casting about for still another body with chemical properties similar to those of tannic acid, pyrogallol was hit upon as a substance worthy of trial. After some preliminary experiments which seemed to indicate that pyrogallol was beneficial upon this soil, providing it had stood some time in contact therewith prior to planting, a plot of the soil in the open was given a treatment with this substance, the dissolved crystals being mixed thoroughly into the upper 15 centimeters in the proportion of about 2,000 parts per million of dry soil. The plat was prepared in September, 1904, and was kept in good physical condition by frequent mixing until December. It then lay over winter. At different times samples of this pyrogallol-treated soil were taken up and tested by growing seedlings in them in the way above described. An experiment lasting from November 4 to December 5, 1904, showed an increase in transpiration of the treated above the untreated soil of 21 per cent. Another test, carried out

from February 13 to February 28, 1905, showed a similar increase of 155 per cent. Still another one, which lasted from February 28 to March 27, 1905, exhibited an increase of 69 per cent. An experiment similar to those just given, but with the pyrogallol added to the soil one week before the seeds were planted, gave parallel results. Three cultures of five baskets each were prepared, containing, respectively, the untreated soil, and the same with the addition of 1,000 and 500 parts per million pyrogallol. These were all allowed to stand one week. Then the seeds were planted and the cultures treated as usual. The experiment lasted from September 28 to October 17, 1904. Table VI presents the data.

TABLE VI.—*Total transpiration, in grams, of thirty wheat plants in Takoma soil with and without pyrogallol.*

Treatment.	Total transpiration.	Percentage increase over untreated soil.
	Grams.	
Takoma soil, untreated	122.8	
Same + 1,000 p. p. m. pyrogallol	244.0	99
Same + 500 p. p. m. pyrogallol	247.0	101

It thus appears that the unproductiveness of this soil is at least partially corrected, not only by adding a small amount of tannic acid but also by pyrogallol.

Another substance which has proved remarkably active in improving the Takoma soil is calcium carbonate. A test of this salt was made from February 14 to March 16, 1905. Dry calcium carbonate was mixed with soil in the proportion of 2,000 parts per million and seedlings were grown in this medium. The total transpiration of thirty seedlings for this period was 256 grams in the untreated soil and 502 grams in the treated, showing a gain in favor of the treated of 96 per cent. An experiment like the last, extending from February 28 to March 27, 1905, showed an increase in transpiration of the treated over the untreated soil of 111 per cent and a similar increase, by green weight, of 71 per cent.

Ferric hydrate, freshly prepared from the nitrate by precipitation with ammonia and thoroughly washed, was mixed into Takoma soil in approximately the proportion of 1 per cent by weight, and the soil thus treated showed great improvement. Two experiments, lasting from February 2 to February 14 and from March 26 to April 8, 1905, exhibited a gain in total transpiration for the treated soil of 27 and 14 per cent, respectively.

The results of the foregoing experiments may be summarized in the statement that the Takoma soil is markedly benefited for the

growth of wheat by admixture of stable manure, green manure, tannin-bearing leaves, tannic acid, pyrogallol, calcium carbonate, and ferric hydrate.

ANALYSIS OF THE FOREGOING RESULTS.

DIRECT EFFECTS.

Addition of stable manure or of vegetable matter to the soil must, a priori, increase the content of the latter in inorganic salts as well as in organic materials. Moreover, it has been repeatedly shown that such addition increases the amounts of these bodies that are water soluble. It is well known to plant physiologists, agriculturists, and horticulturists that green plants, in general, use as food constituents not only carbon dioxide from the air and water from the soil, but also, from the latter source, the elements potassium, calcium, magnesium, and iron, and the acid radicals of nitric, sulphuric, and phosphoric acids. It is also understood, of course, that in order to enter the plant and become available for use in metabolism, all substances must be in aqueous solution, so that the results obtained by adding manure, leaves, or calcium carbonate to the soil might be supposed to be due to a direct increase in some soluble constituent necessary to the plant. This explanation, as far as mineral salts are concerned, is rendered improbable by the fact that agricultural fertilizers have very little or no effect upon this particular soil. A number of wire-basket tests of fertilizers were made. The experiment lasted from December 2 to December 31, 1903. To each of 500 grams of dry soil was added 10 milligrams of one or more of the fertilizer constituents, potash, nitrate, and phosphate, in the form of the salts named in the following table, thus giving for each constituent a concentration of 20 parts per million. Three baskets of six plants each were used for each treatment. The total transpiration for the twenty-nine days is given below:

TABLE VII.—*Total transpiration from eighteen plants for twenty-nine days in Takoma soil with various fertilizers.*

Treatment.	Weight of water transpired.
	Grams.
Takoma soil, untreated	227.8
Same+$NaNO_3$	245.9
Same+$Ca_3(PO_4)_2$	226.7
Same+K_2SO_4	211.6
Same+$Ca_3(PO_4)_2$+$NaNO_3$	255.3
Same+$NaNO_3$+K_2SO_4	269.7
Same+$Ca_3(PO_4)_2$+K_2SO_4	210.8
Same+K_2SO_4+$NaNO_3$+$Ca_3(PO_4)_2$	234.6
Same+K_2SO_4+$NaNO_3$+$CaH(PO_4)_2$	226.8

The only one of these fertilizers which benefited this soil is sodium nitrate, and that to a very slight amount. It thus appears that the cause of sterility here is something other than lack of nutrient salts.

It is barely possible that certain organic compounds may be absorbed from the soil, and may, under certain conditions, be used directly by ordinary green plants just as they are used by saprophytes and parasites, but it is highly improbable that this is an important consideration under ordinary conditions of growth. The question has never been thoroughly investigated, and the evidence in favor of the use by the plant of organic matter is extremely fragmentary and inconclusive.

Besides adding soluble substances directly, the treatment of the soil, as outlined above, may, of course, increase the solubility of certain of the soil constituents by chemical action upon very slightly soluble compounds. Thus the observed beneficial effect might be explained on the ground that more of the soluble forms of substances essential to plant growth are present in the manured soil than in the untreated one, and that therefore the former soil supports the greater growth. The fertilizer test just described makes this explanation extremely improbable in general. It will be considered further under "Indirect effects."

In tannic acid and pyrogallol we have two closely related substances, derivatives of benzene, and composed solely of carbon, hydrogen, and oxygen. They contain no nitrogen. Thus the only way in which these substances could be of *direct* effect upon the plant is to furnish an organic substance which is absorbed by the roots and which hastens growth. This, as has been pointed out, is extremely improbable.

The marked increase in fertility which follows the treatment of the soil with calcium carbonate can not be explained by assuming that the untreated soil is deficient in calcium, for the water extract of this always contains calcium to an amount equivalent to at least 10 parts per million of dry soil, and a number of analyses of fertile soils in New Jersey and Maryland,[a] made by Taylor and Mooney, show even less of this element than the above figure would indicate. These analyses were made in exactly the same manner as were those of the present soil. Conclusive evidence that $CaCO_3$ is not effective here through an increase in the amount of calcium will be presented farther on (see p. 26).

Ferric hydrate is extremely insoluble, as is well known. It can increase the amount of soluble iron in the soil only to an infinitesimal degree. Moreover, the amount of iron necessary for plant growth is extremely small, and it is probable that no natural soil is deficient

[a] Bul. No. 22, Bureau of Soils, U. S. Dept. Agr., 1903, pp. 23–33.

in this element. The soil with which we are dealing contains more iron than many other soils which are agriculturally fertile.

INDIRECT EFFECTS.

In the last paragraphs it has been shown that the beneficial effect of stable manure, green manure, leaves of sumac, oak, etc., tannic acid, pyrogallol, calcium carbonate, and ferric hydrate are probably not due to the direct introduction of plant nutrient materials into the soil. An indirect effect through chemical change and an alteration in the equilibrium of the soil components is possible, as has already been suggested. Thus, these substances might react with certain of the soil minerals to increase the amount of soluble potassium or other food constituent for plants. The complexity of the soil system and our extreme ignorance regarding it render the question just suggested impossible of a definite and conclusive answer by means of experiments carried out upon the soil itself.

But, as was pointed out in Bulletin 23 of this Bureau,[a] the relatively good or bad properties of a soil, as shown by the growth of the plants upon it, are transmitted to the aqueous extract of that soil, so that wheat seedlings grown in an extract of a poor soil will exhibit much less growth in a given time than those in a similar extract of a good soil. This fact offered a possible method for attacking the problem here presented. An extract of Takoma soil was prepared in the conventional way devised in this Bureau.[b] Five parts by weight of soil were stirred for three minutes with 6 parts of distilled water and then allowed to settle for twenty minutes. The extract was then poured off and filtered, under pressure, through a thoroughly clean Pasteur-Chamberland filter tube, after which it was usually aerated by violent shaking, although the filtering process itself is an efficient means to this end. The soil solution thus obtained, with various treatments, was used as culture medium for wheat seedlings. The cultures were prepared in large-mouthed bottles of black glass, capacity 60 cubic centimeters, with four plants in a bottle. The seedlings were germinated in sand until the shoots were about 2 centimeters in length and were then fixed in openings cut in the margins of cork stoppers in such manner that when the latter were placed in the bottles the roots dipped into the liquid, while the seeds were just above its surface. The arrangement was such that practically no water was lost by the culture except through transpiration. The bottles were weighed in groups of three at intervals of two or three days and their loss recorded. The total transpiration was obtained

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[a] Bul. 23, Bureau of Soils, U. S. Dept. Agr., 1904, p. 33 et seq.

[b] Bul. 22, Bureau of Soils, U. S. Dept. Agr., 1903, p. 37.

at the end of the experiment by adding the transpirations for the several periods. The solutions were replaced by fresh ones similarly prepared every four or five days.

Roots of seedlings grown in the untreated extract are short and have relatively but few branches. The tops appear normal, but are of small size. When aqueous extract of stable manure is added to the soil extract the roots are profusely branched, and the primary ones attain a much greater length than they do in the untreated soil extract. The tops also are much larger in the treated extract, and the amount of total transpiration is greatly increased. It is thus seen that manure solution has identically the same effect in the soil extract that manure has in the soil itself.

Pyrogallol also has the same effect in the extract that it does in the soil. An experiment lasting from March 20 to April 4, 1905, in which untreated extract of Takoma soil was compared with the same extract to which this chemical had been added in the proportion of 10 parts per million will illustrate this. Thirty-six seedlings were grown in each solution, the transpiration data being taken for each of three groups of three bottles each; thus each culture as given below contained twelve plants.

Table VIII.—*Growth of wheat in extract of Takoma soil with and without pyrogallol.*

Treatment.	Total transpiration.			Grand total transpiration.	Average.
	Culture No. 1.	Culture No. 2.	Culture No. 3.		
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Grams.*
Takoma soil extract	44.2	46.5	47.1	137.8	45.9
Same + 10. p. p. m. pyrogallol	60.5	62.7	67.5	189.7	63.2
Percentage increase due to pyrogallol	37	35	44	37	38.6

The data for percentage increase, given in the last line of the above table, excepting the last quantity of that line, are derived by dividing the quantity in the second line by that in the first, subtracting unity and multiplying the result by 100. Since the individual cultures vary among themselves, they are numbered in the order of the magnitude of their total transpiration. The average percentage increase is merely the average of the three percentage increases for the separate cultures. The data show that the total transpiration of the thirty-six plants was increased 37 per cent by treatment of the extract with pyrogallol, while the average increase thus obtained for the three separate cultures was 38.6 per cent. It was shown by further experimentation that a larger amount of pyrogallol could not be used in

this way without injurious effect upon the plants. Larger amounts were used, however, in a special way, to be described later.

When calcium carbonate is added in excess to the bottles of soil extract a still more marked improvement of the plants is exhibited. Data from several experiments with this substance are given in Table IX. The actual transpiration figures will be omitted from this and the tables which are to follow, the percentage increase being the only quantity which is of interest.

TABLE IX.—*Percentage increase in total transpiration from wheat plants in Takoma soil extract, with excess of $CaCO_3$, compared with transpiration from plants in untreated extract.*

Number and duration of experiment.	Percentage increase in transpiration.				
	Culture No. 1, 12 plants.	Culture No. 2, 12 plants.	Culture No. 3, 12 plants.	Average.	Entire series.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
I. June 17 to June 25, 1904	112	109		110.5	109
II. March 28 to April 17, 1905	62	60	104	75.3	77
III. March 28 to April 17, 1905	194	196	188	192.6	190
IV. March 31 to April 18, 1905					[a] 74

[a] The data for the individual cultures in this experiment were not kept separate.

In this table the duration of the experiment is given by the two dates; each culture consisted of twelve plants, in three bottles, and they are numbered as in the experiment with pyrogallol described above. In the column marked "Average" the figures denote the average of the percentage increases of the several separate cultures. In the column marked "Entire series" are given the percentage increases in total transpiration for the period, considering the whole series as a single culture. In the cultures with calcium carbonate the roots grow exceedingly long and are well branched.

With an excess of ferric hydrate added to the extract of Takoma soil the result is just as marked. In a number of experiments the extract was shaken thoroughly with ferric hydrate and then filtered, the plants being grown in the filtrate. From these it appears that extract so treated has been much improved, although not to such a degree as in the case where the insoluble body is left in the extract while the plants are growing. This fact will be discussed later. Data from seven experiments, the extracts of two of which were filtered free of ferric hydrate, are given in Table X. They are tabulated as in the preceding.

TABLE X.—*Percentage increase in total transpiration from plants in Takoma soil extract treated with ferric hydrate compared with transpiration from plants in untreated extract.*

Number and duration of experiment.	Percentage increase in transpiration.				
	Culture No. 1, 12 plants.	Culture No. 2, 12 plants.	Culture No. 3, 12 plants.	Average.	Entire series.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
I. June 17 to June 25, 1904	131	91	----------	111	101
II. June 18 to June 25, 1904	83	151	----------	117	112
III. March 20 to April 4, 1905	83	112	138	111	105
III (a). Same as III, but $Fe(OH)_3$ filtered out	55	59	81	65	66
IV. March 28 to April 17, 1905	75	63	108	82	74
V. March 31 to April 18, 1905	----------	----------	----------	----------	[a] 41
V (a). Same as V, but $Fe(OH)_3$ filtered out	----------	----------	----------	----------	[a] 31

[a] Data for individual cultures not kept separate.

Another insoluble substance which has much the same effect as ferric hydrate, though to a somewhat less extent, is carbon black. The form used is very finely divided carbon, prepared from the burning of petroleum. It was thoroughly washed before using and contains practically no water-soluble material. It was used in the cultures in the same manner as were ferric hydrate and calcium carbonate. Soil extract was also treated by shaking with carbon black and then filtering off the solution, as in the case of ferric hydrate. Its effect when used in this way is quite marked. Data from six experiments with this body are presented below; two of these experiments were carried on with extract filtered from carbon after the latter had been added and shaken up thoroughly.

TABLE XI.—*Percentage increase in total transpiration from plants in Takoma soil extract treated with carbon black, compared with transpiration from plants in untreated extract.*

Number and duration of experiment.	Percentage increase in transpiration.				
	Culture No. 1, 12 plants.	Culture No. 2, 12 plants.	Culture No. 3, 12 plants.	Average.	Entire series.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
I. October 3 to October 17, 1904	----------	----------	----------	----------	[a] 13
II. March 20 to April 4, 1905	57	54	59	56.6	57
II (a). Same as II, but carbon filtered out	27	24	27	26.0	26
III. March 28 to April 17, 1905	59	38	30	42.0	48
IV. March 31 to April 18, 1905	----------	----------	----------	----------	[a] 30
IV (a). Same as IV, but carbon filtered out	----------	----------	----------	----------	[a] 5

[a] Data for individual cultures not kept separate.

From the results of the experiments just presented and of others of similar nature, it is evident that stable manure, pyrogallol, calcium carbonate, ferric hydrate, and carbon black all bring about a great improvement in the extract of Takoma soil. Since the extract contains no undissolved substances, it is evident that these beneficial

effects can not be ascribed to a setting free of insoluble bodies in the soil. Also, since carbon black and ferric hydrate add no soluble matter to the extract, since the lime salt can not have its beneficial effect through increase in soluble calcium (for reasons in part already given and in part to be presented below), and since the effect of pyrogallol can not plausibly be attributed to this chemical itself, it becomes certain that the bad properties of this soil do not arise from absence of any materials. The only alternative remaining is that these bad properties are due to the *presence* of *deleterious substances* which check the growth of the wheat and which are altered or removed by the various treatments already mentioned.

DELETERIOUS SUBSTANCES IN THE SOIL.

The injurious bodies present in this soil are changed or removed by treatment with tannic acid, pyrogallol, calcium carbonate, ferric hydrate, and carbon black. It appears probable that the first two of these substances act chemically in some way upon these bodies. Since pyrogallol is injurious in large amounts in solution, an attempt was made to allow it to act upon the soil extract at rather high concentration and then to alter the excess of pyrogallol in such manner as to make it noninjurious. The reagent was added to the Takoma soil extract in varying concentrations and allowed to stand for twelve hours, with frequent shaking. Then enough trimethylamine was added to each treated extract to neutralize the pyrogallol, after which cultures were prepared with the extracts. The results of an experiment of this sort are given in Table XII. The seedlings grew from March 28 to April 17, 1905. Twelve plants were used in each of three cultures. Data are given as in previous tables.

TABLE XII.—*Total transpiration of thirty-six wheat plants in Takoma soil extract treated with pyrogallol and then with trimethylamine.*

Treatment.	Percentage increase over Takoma soil extract untreated.				
	Culture No. 1, 12 plants.	Culture No. 2, 12 plants.	Culture No. 3, 12 plants.	Average.	Entire series.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Takoma soil + pyrogallol 1 p. p. m., neutralized	48	50	49	49.0	47
Same + pyrogallol 10 p. p. m., neutralized	54	39	51	48.0	47
Same + pyrogallol 20 p. p. m., neutralized	82	64	62	69.3	60
Same + pyrogallol 40 p. p. m., neutralized	57	37	52	48.6	45
Same + pyrogallol 60 p. p. m., neutralized	45	35	39	39.6	39
Same + pyrogallol 80 p. p. m., neutralized	52	33	44	43.0	56
Same + pyrogallol 100 p. p. m., neutralized	82	62	62	68.6	67
Second average				50.87	

From this table it is clear that the amount of pyrogallol used has little or no effect upon the result as long as the excess is neutralized by

trimethylamine, neither has the amount of the ammonia derivative any effect as long as it is neutralized by pyrogallol, and since the amount of the compound formed by this mutual neutralization must increase with the amounts of the reacting bodies, this also has no effect. The results of this experiment agree very well with those obtained with 10 parts per million of pyrogallol alone. (See p. 22, ante.) Therefore the beneficial effect must be ascribed to this chemical, and it may be concluded that this effect amounts to about 50 per cent in all concentrations. This points strongly to the idea that the beneficial effect is not due to the action of the pyrogallol itself upon the plant, but to some effect which it has upon the toxic substances in the extract.

Calcium sulphate was used on the soil directly, the calcium being in amount chemically equivalent to that used in case of calcium carbonate (2,000 parts per million), and the two were compared, the result showing a beneficial effect for the former of only 20 per cent as compared with one for the latter of 131 per cent. This seems to set aside finally any question as to the beneficial effect of calcium itself acting as a nutrient material, for calcium sulphate is considerably more soluble than calcium carbonate. Calcium chloride was also used on the soil in varying concentrations, but without any beneficial result. It appears, then, that calcium carbonate has its effect in acting as such upon toxic bodies in the soil, and not at all in increasing the amount of calcium.

That ferric hydrate and carbon black have much the same effect whether they are left in the soil extract or are entirely removed from it before the plants are placed therein, suggested that the effect of these bodies may be due to absorbent action. In certain cases such insoluble substances are known to absorb (by adsorption or otherwise) toxic bodies from solutions, and this to such an extent as to render the solutions nontoxic.[a]

It seems very probable that, whether in the soil or in its aqueous extract, these bodies simply remove from solution the injurious substances contained in the soil.[b] The process of removal may or may

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[a] Especially see True, R. H., and Oglevee, C. S.: The effect of the presence of insoluble substances on the toxic action of poisons, Science, II, **19**: 421–424; Bot. Gaz., **39**: 1–21, 1905. Dandeno, J. B.: The relation of mass action and physical affinity to toxicity, Am. Jour. Sci., II, **17**: 437–458, 1904. Breazeale, J. F.: Effect of certain solids upon the growth of wheat in water cultures. About to appear in Bot. Gaz., 1905.

[b] The absorptive properties of soils themselves may play some part in determining whether they shall be fertile or infertile. Many organic dyes, such as methylene blue, eosin, etc., are completely removed from their solutions by shaking the latter with certain soils. This power to remove such dyes seems to vary markedly with different soils, as well as with the different dyes, but this whole matter still awaits investigation.

not be accompanied by some chemical change, as of oxidation; this question has not been investigated.

Although the data already presented seem sufficient to prove the presence in this soil of some substance or substances toxic to wheat plants, yet the following experiments make the evidence much stronger in this direction. A clean glass sand was used in basket cultures and was watered with Takoma soil extract. This was compared with similar cultures of the soil itself. The experiment consisted of two baskets of each medium and ran from November 19 to December 15, 1904. The two cultures gave an increase in total transpiration in favor of the sand of 47 and 43 per cent, respectively. Since the soil contained unquestionably more soluble salts than did the untreated sand, and since by watering the latter with the extract of the former it must be impossible to furnish it with as much of these salts as would occur in the constantly saturated solution of the soil itself, the soil in this experiment must have contained more nutrient salts than did the sand. But organic matter, as well as salts, must be present in greater amount in the soil itself than in the sand watered with soil extract. Thus it must be concluded that in this experiment the soil contains more injurious substances than does the sand and that these are active in stunting the plants in spite of the larger amounts of nutrient salts present.

Another experiment which offers conclusive evidence in this regard was carried on with water cultures. A nutrient solution containing the necessary salts for plant growth [a] and made up with distilled water was used as a control. A similar solution made up with Takoma soil extract instead of distilled water was compared with this. Distilled water from the same distillation was used in preparing the soil extract and the nutrient solution. Twenty seedlings were used in each case. The experiment ran from November 26 to December 9, 1904, and gave total transpirations of 249.7 grams for the control and 212.6 grams for the other, a percentage increase of 17 per cent in favor of the nutrient solution made from water. The

[a] The nutrient solution used in this and in certain of the following experiments contained the following salts in the proportions given below. The concentrations are given both in terms of chemical equivalents and in parts per million:

Salt.	Gram equivalents per liter.	Parts per million.
Calcium sulphate, $CaSO_4$	0.0005	34
Magnesium acid phosphate, $MgHPO_4$	.0005	30
Potassium carbonate, K_2CO_3	.0005	34
Sodium nitrate, $NaNO_3$	.0005	42
Ammonium chloride, NH_4Cl	.0005	27
Ferric nitrate, $Fe(NO_3)_3$	.000062	5
Total parts per million		172

solution made with soil extract must have contained nutrient salts in considerably greater amount than did the other, inasmuch as salts were contained in the soil extract before the chemicals were added. The only possible explanation of this difference in growth is on the hypothesis of toxic substances stated above.

Another experiment with water cultures bears on this consideration. A nutrient solution was prepared with distilled water and was used as a control. An extract of Takoma soil made with this solution instead of with water and a similarly prepared extract of Hagerstown clay (an agriculturally fertile soil), were compared with this control. Twenty-four seedlings were used in each case and the experiment lasted from November 28 to December 9, 1904. The total transpirations for this period are shown in Table XIII.

TABLE XIII.—*Total transpiration, in grams, of 24 seedlings grown in nutrient solution and in soil extracts prepared with nutrient solution in place of water.*

Medium.	Transpiration.	Decrease.
	Grams.	*Per cent.*
Nutrient solution	139.1	
Takoma soil extract prepared with nutrient solution	82.5	41
Hagerstown clay extract prepared with nutrient solution	109.2	21

These results show clearly that by extracting the Takoma soil with the nutrient solution the latter was greatly injured. That the fertile soil had only about half as much injurious effect as did the other is to be explained on the supposition that it contains only relatively small amounts of toxic bodies, while the Takoma soil contains large amounts. The supposition that the Takoma soil absorbed more salts from the solution than did the Hagerstown clay, thus rendering the solution from it too weak for supplying proper nutrient, is possible in this particular case. However, it is probable that the Hagerstown clay possesses a greater absorptive power for salts than does the Takoma soil.

Altogether the data point definitely to the conclusion that the Takoma soil is unproductive for wheat because of the presence therein of toxic bodies and not because of the absence of any plant food materials.

ON THE CHARACTER OF THE DELETERIOUS SUBSTANCES IN TAKOMA SOIL.

That the toxic substance or substances of Takoma soil are soluble in water is shown by the fact that they are present in the aqueous soil extract. They are present, however, in such small amount that a direct chemical investigation of their nature is for the present out of the question. These toxic substances are not destroyed by boiling,

nor are they driven off nor volatilized with steam, but they are concentrated by evaporation of the soil extract. This was shown by the following experiment: Extract of Takoma soil was evaporated by boiling to one-tenth of its original volume. The concentrated extract thus obtained was used in water cultures in comparison with the original extract. Carbon black was added to duplicate cultures of these two solutions. The experiment lasted from April 8 to April 24, 1905. Table XIV presents the data.

TABLE XIV.—*Total transpiration, in grams, of 24 wheat seedlings grown in Takoma soil extract and in the same concentrated to one-tenth its original volume, both with and without carbon black.*

Medium.	Transpiration.	
	Untreated.	With carbon black.
	Grams.	*Grams.*
Takoma soil extract	25.2	38.0
Same, evaporated to one-tenth its volume	15.6	42.8

From these data it is at once evident that concentrating the extract to one-tenth its original volume makes it much more toxic to the plants. Further, the effect of carbon black is even more marked upon the concentrated extract than upon the natural. Perhaps the toxic substances are altered by boiling, so as to be more thoroughly absorbed by the carbon black, but no further investigation of this question has as yet been attempted.

That the toxic bodies of Takoma soil are mineral or inorganic in their nature seems very improbable. The large amount of organic matter present suggested that they might belong to this class. To test this question, a large sample of the soil was baked in an oven until the organic matter was quite thoroughly charred. Upon being moistened again it was found to have become decidedly acid to litmus paper, probably by the production of organic acids during the charring process. A sample of the charred soil was tested in basket cultures, but was found to be much more toxic than it was originally, as should be foreseen from its acidity. However, after standing in a box open to the weather for six weeks the acidity of the charred soil had decreased markedly, and basket cultures were again set up with it. This time the plants upon the charred soil surpassed those on the untreated by 42 per cent. Of course, it is possible that this beneficial effect may have been due to changes in the soluble salt content of the soil which occurred during the heating process.

In order to settle this question it was necessary to resort again to the use of soil extract. A portion of aqueous extract of Takoma soil was evaporated to dryness, the residue charred, and then returned to solution in its original volume. The solution thus prepared was used

in water cultures, and the growth of the plants was compared with that of a control culture in natural extract. This experiment consisted of twenty-four plants grown nine days, and the total transpirations for the period were 38.6 grams for the control and 48.3 grams for the culture in the solution of the charred residue. This indicates an increase in the growth of the plants of 25 per cent, due to evaporating and charring the extract. The same sample of distilled water was of course used throughout the experiment. The test was repeated with similar results. In these experiments the increase in fertility can not be ascribed to any indirect effect of heat upon the chemical equilibrium of the soil as regards nutrient salts. The indication is, therefore, that the toxic property of this soil is at least partially due to organic material which is destroyed or essentially altered by charring. It seems highly probable that all the toxic bodies here active are organic in their nature.

The fact that this soil is acid to litmus, but not to methylorange, and that the acidity is probably due to organic acids, has been stated previously. Its aqueous extract is also acid, but not to so marked a degree. After boiling to expel carbon dioxide the extract, prepared in the way already described, is acid to an extent approximating 2/16,000 to 4/16,000 normal, phenolphthalein being used as indicator and the titration being made with N/100 potassium hydrate solution.

It was suggested that the toxic property of this soil and of its extract might be due to this acidity and an investigation of this point was deemed important. If the above suggestion were true it might be possible that calcium carbonate had its beneficial effect upon this soil and extract by merely neutralizing the excess of acid present. To test whether this was correct, the extract was made alkaline with several soluble alkalies and then compared by means of wheat cultures with the untreated extract. By this treatment ammonia and trimethylamine were found to be without effect, while sodium carbonate, sodium hydrate, and barium hydrate increased the growth of the plants about 50 per cent above that of the control in untreated extract. The fact that ammonia and its derivative trimethylamine produce no effect upon the growth of the plants seems at once to show that the toxicity of the soil is not due to its acid properties, for it is inconceivable that these acid properties are not neutralized in the extract by these alkaline bodies. Calcium carbonate used in excess gave, in these experiments, an increase of about 120 per cent, showing that there must be involved in the beneficial effect of the latter salt something other than such neutralization of the acid of the extract as is obtained from sodium carbonate, etc. Putting aside for the time being the evidence from ammonia and trimethylamine, it was suggested that possibly the excess of calcium carbonate might

be effective through a continual neutralization of acid products from the plant roots as fast as these might be given off. To test this idea, the extract was again made barely alkaline with each of the more soluble alkalies named above, sufficient phenolphthalein having been added to give a clear indication of alkalinity. Daily examination of the cultures showed the gradual production of acid by the roots, but this was corrected daily by repeated additions of the respective alkalies. These cultures were carried on parallel with two others, one with excess of calcium carbonate, the other with the natural soil extract. In this series the soluble alkalies showed no greater relative effects than were produced by the single neutralization described above. This indicates that the greater beneficial effect of calcium carbonate can not be ascribed to the fact that it keeps the nutrient medium constantly alkaline, but that an explanation of its effect must be sought elsewhere, probably in its absorptive power.

The well-marked though comparatively small beneficial effect of several of the more soluble alkalies tested would seem to indicate that the toxicity of Takoma soil may, nevertheless, be due in some part to its acid properties. But this supposition is rendered very doubtful by another fact discovered in this connection, namely, that the acidity of the extract is not altered by shaking with carbon black and then filtering out the carbon. But this very carbon treatment benefits the extract markedly for the growth of wheat. Altogether it seems probable that while the toxic bodies may have acid properties, yet their toxicity is not due to these. In the language of the dissociation hypothesis, the toxicity is probably not due to hydrogen ions, and those of the more soluble alkalies which are beneficial may have their effect through some other action than that of neutralizing acids.

The possible mode of action of pyrogallol was considered also in connection with this problem of acidity. Ten wheat plants were grown from April 20 to May 6, 1905, in extract of Takoma soil in which 40 parts per million of this chemical had been allowed to remain, with frequent shaking, seven hours and then the excess neutralized, as before described, with trimethylamine. This culture was compared with a similar control in untreated soil extract. At the end of the experiment the acidity of each solution was determined by titration with N/100 potassium hydrate solution. The results showed the usual beneficial effect upon the plant due to pyrogallol, but the acidity of the two solutions was practically the same at the time of titration, being 3N/16000 for the untreated extract and 4N/16000 for the other. This shows clearly that the effect of pyrogallol is not due to any alteration in the acidity of the extract.

Finally, conclusive proof that the mere fact of acidity has nothing directly to do with the toxic properties of this soil was given by several experiments on the soil itself. An example of one of these

experiments is here given. On April 19, 1905, were prepared three paraffined wire baskets of Takoma soil and three baskets of the same soil with each of seven different treatments, as shown in Table XV. After these baskets had stood one week the soil was emptied out of one from each set of three and a water extract prepared from it in the usual way. These eight extracts were boiled five minutes to expel carbon dioxide and the acidity of each was then determined by titrating with N/100 potassium hydrate solution, as above described. Wheat was planted in the remaining baskets on April 26, the baskets were sealed at the top on May 8, and the transpirations of the cultures were taken from the latter date until May 22. At the end of the experiment the soil of the cultures was separated from the roots and an extract made, boiled, and tested for acidity, as before. All the data are given in Table XV.

TABLE XV.—*Transpiration from twelve wheat plants in Takoma soil with various treatments, and acidity data for the soil before planting and after the plants had grown.*

Medium.	Total transpiration.	Acidity of soil extract in terms of normal acid.	
		At planting.	End of experiment.
	Grams.		
Takoma soil	83.0	3N/16,000	3N/16,000
Same + 500 parts per million pyrogallol	95.6	2N/16,000	3N/16,000
Same + 100 parts per million pyrogallol	93.8	2N/16,000	3N/16,000
Same + 1 part per million tannic acid	87.3	4N/16,000	3N/16,000
Same + 2,000 parts per million Ca as $CaCO_3$	130.2	2N/16,000	6N/16,000
Same + 2,000 parts per million Ca as $CaSO_4$	94.0	8N/16,000	21N/16,000
Same + 1 per cent $Fe(OH)_3$	108.2	N/16,000	6N/16,000
Same + 5 per cent carbon black	107.3	N/16,000	3N/16,000

It will be observed that the transpiration figures show a slight beneficial effect due to tannic acid, pyrogallol, and calcium sulphate, and a well-marked effect due to calcium carbonate, ferric hydrate, and carbon black. An inspection of the acidity data shows clearly that the differences in growth shown by transpiration are not at all correlated with the differences in acidity.

It is a matter of common experience that many soils will finally become unproductive for certain plants if the latter are grown upon them for a number of years in succession. Such soils generally remain, however, quite productive for other plants, especially for plants of a markedly different nature. These facts have usually been explained on the ground that the repeated crop has exhausted the soil of those plant-food materials requisite for the growth of this plant, or altered the proportions of these salts so as to result in an unbalanced ration, and that the later crops are stunted by starvation. Other nonrelated plants are supposed to require different food materials; hence

they can still thrive on a soil which has been exhausted by the first form.

On account of the general uniformity in requirements of nutrient materials by the great majority of agricultural plants, the explanation just given appears improbable. The fact that productive and unproductive soils generally give about the same amounts of salts in their aqueous extracts[a] strengthens this view. The discovery of the presence of injurious material in Takoma soil suggested that what is commonly termed an "exhausted soil" might be one simply containing a relatively large amount of such bodies, and that the exhaustion of a soil by repeated cropping might mean that these toxic substances increase in the soil from year to year if the same plant is grown thereon, while they do not thus increase if a proper rotation of crops is followed. If such were the case it might be that the injurious substances are excreted from the plant roots, different forms excreting different bodies, and the latter being toxic to the form excreting them, but not so toxic to nonrelated forms. To investigate this possibility a number of experiments have been carried out.

The effect of replanting Takoma soil with wheat was determined in basket cultures. Five baskets of the soil were prepared and plants were grown in them from December 21, 1904, to January 18, 1905. The plants were then removed, the soil was emptied out, mixed thoroughly, and then returned to the baskets. The second planting followed, the plants growing from January 19, to February 10, 1905, and a control with fresh soil was also carried on. Two other plantings followed this in the same manner, each with a control in fresh soil. Data for the whole series of four plantings are given in Table XVI.

TABLE XVI.—*Total transpiration and green weight of thirty wheat plants in unused Takoma soil and in the same replanted three successive times, together with percentage decrease due to "exhaustion" of the soil.*

Number of crop and duration of growth.	Fresh soil control.		Used soil.		Decrease, data for fresh soil being considered as unity.	
	Total transpiration.	Green weight.	Total transpiration.	Green weight.	Total transpiration.	Green weight.
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Per cent.*	*Per cent.*
First planting, Dec. 21, 1904, to Jan. 18, 1905	337.9	4.3				
Second planting, Jan. 19, 1905, to Feb. 10, 1905	284.8	4.3	161.8	2.3	43	47
Third planting, Feb. 15, 1905, to Mar. 11, 1905	430.1	4.3	199.1	2.3	56	47
Fourth planting, Mar. 15, 1905, to Apr. 7, 1905	430.9	5.4	136.9	2.5	68	54

[a] Bul. 22, Bureau of Soils, U. S. Dept. Agr., 1903.

It appears from these data that the soil lost during the growth of the first crop nearly one-half of its productiveness, and that during the growth of the first three crops it lost considerably over one-half, so that the growth of the plants was finally less than one-half as great as it was on fresh soil at the same time.

To determine whether this loss was probably due to decrease in food materials or to the formation of some toxic substances and acid, washed quartz sand was tested in the same way. A series of five basket cultures of a clean glass sand was run parallel to a similar series of the same sand, which had previously grown wheat for twenty-one days. The experiment extended from April 8 to May 13, 1905. The old sand gave a total transpiration of 115.7 grams, while the fresh gave 254.1 grams. Thus this old sand had been "exhausted" to the extent of a decrease in transpiration of 54 per cent. In the same experiment ferric hydrate was added to another series of five baskets of old sand, with a total transpiration of 239.2 grams. The insoluble body had renovated the soil to an extent such that when so treated the plants in it exhibited a total transpiration only 6 per cent lower than those in the fresh sand. It thus appears that the growth of wheat upon a soil will decrease its productiveness, and that this decrease may well be due to an excretion or formation of such injurious material in the soil as can be rendered harmless by ferric hydrate.

From the above experiments it seemed probable that the toxic substances might increase in amount during the growth of the first crop, and that if the correcting substances were present in the soil from the start, a greater growth of this first crop might be obtained. An experiment testing this suggestion was carried out from February 2 to February 18, 1905. Ferric hydrate was thoroughly mixed with glass sand and compared with the same sand untreated. Five baskets were used in each case. The total transpiration of the plants in the untreated medium was 276.9 grams, while that from the other culture was 364.9 grams, showing a well-marked gain for the ferric hydrate. In order to determine whether the presence of ferric hydrate might influence the amount of water-soluble salts in the sand, a water-extraction analysis was made of each medium at the end of the experiment, with the results shown in Table XVII. Parts per million of dry soil are given.

TABLE XVII.—*Analysis of water extract of glass sand with and without ferric hydrate, after crop had grown.*

[Parts per million of dry soil.]

Medium.	Nitrates (NO_3).	Potassium (K).	Calcium (Ca).	Phosphate (PO_4).
Untreated glass sand	0.6	3.6	10.7	12.5
Same + ferric hydrate	.6	3.9	10.7	12.2

From these data it is evident that the ferric hydrate can not be considered as having an indirect effect on the amount of soluble salts. Another experiment exactly similar to the above lasted from February 17 to March 15, 1905, and gave transpirations of 248.4 grams and 259.3 grams for the untreated and treated sand, respectively. Still another, from March 13 to April 8, 1905, gave total transpirations of 92.6 grams for the untreated and 138 grams for the treated.

It has been found also that nutrient solutions which have been previously used for growing plants give a much poorer growth on second planting than does a freshly made solution of the same nature. But addition of ferric hydrate and carbon black renovate the used solution so that it produces nearly as good plants as the fresh one. An example from a number of experiments in this regard may be given here. The used nutrient solution was prepared by growing plants in a freshly prepared solution for fourteen days. Thirty plants were used for 500 cubic centimeters of solution. Then these plants were removed and new cultures in this used solution with addition of ferric hydrate and carbon black were compared with a new culture in the same solution untreated. The experiment lasted from May 18 to June 5, 1905, each culture consisting of 10 plants in 240 cubic centimeters of the medium. The data of transpiration are given in Table XVIII.

Table XVIII.—*Total and relative transpiration of ten wheat plants in used nutrient solution treated and untreated.*

Medium.	Transpiration.	Increase.
	Grams.	*Per cent.*
Used nutrient solution	62.5	
Same + ferric hydrate	95.6	53
Same + carbon black	101.6	63

The experiment described above for soils, of placing the insoluble substance in the fresh medium and then growing plants in it, was tried for water cultures also. Total transpirations from such a test are given in Table XIX. It extended from April 4 to April 20, 1905, and contained 24 seedlings for each treatment.

Table XIX.—*Total and relative transpiration of twenty-four wheat plants in fresh nutrient solution treated and untreated.*

Medium.	Transpiration.	Increase.
	Grams.	*Per cent.*
Nutrient solution	131.4	
Same + ferric hydrate	175.3	33
Same + carbon black	166.6	27

In the last case ferric hydrate appears to be more efficient in correcting the solution than carbon black. This is generally found to be true, but the effect is well marked in both cases, and occasionally, as in the example with used solution, carbon black surpasses the other solid. It is seen from these two experiments that, while ferric hydrate and carbon black have marked beneficial effects both in the used and fresh nutrient solution, the improvement due to these bodies is about twice as great in the case of the used solution as in the fresh. This seems to indicate quite clearly that, in these experiments, the toxic material which the solids must be supposed to absorb have their origin in the growing plants themselves. If this is the case, the used solution should contain at the beginning of the second culture approximately as much toxic material as will be given off by the roots of the second lot of plants. Thus the solids should be expected to absorb about twice the quantity of such material in the former of these two experiments as they do in the latter, and the relative beneficial effects exhibited in the two experiments should be in about the same order as shown in the actual results.

An experiment somewhat similar to the ones just described was carried on with Takoma soil extract. One culture was continued with addition of nothing but distilled water from time to time. The second had its soil extract replaced weekly by a freshly made extract. The third contained ferric hydrate at the start, and this substance was filtered out weekly and replaced with fresh, the solution remaining the same, excepting for addition of distilled water to make up for that given off by the plants. The experiment lasted from April 21 to May 6, 1905. The results are given in Table XX.

TABLE XX.—*Total transpiration, in grams, of thirty-two wheat plants grown in extract of Takoma soil, with various treatments.*

Medium.	Transpiration.
	Grams.
Takoma soil extract, continual	92.3
Same, renewed weekly	151.8
Same + ferric hydrate, this substance being renewed weekly	210.3

The renewal of the extract prevents the accumulation of any substances which may have exuded from the wheat roots. It also increases the amount of soluble salts available for use by the plants, since these are renewed with the extract. But in the last culture no nutrient salts were added and yet the increase in growth was much greater in this case than in the second.

In order to make it absolutely certain whether the ferric hydrate might have any effect other than that upon some poisonous substance,

cultures were grown with distilled water in place of a nutrient solution. A series similar to the one with nutrient solution above, and lasting for the same time, was grown in distilled water from the laboratory still and in the same medium, with addition of ferric hydrate and of carbon black. The total transpirations are presented in Table XXI.

TABLE XXI.—*Total transpiration, in grams, of twenty-four wheat plants, in ordinary distilled water, treated and untreated.*

Medium.	Transpiration.
	Grams.
Ordinary distilled water	21.7
Same + carbon black	39.8
Same + ferric hydrate	40.0

Another series carried out at the same time with the same number of plants was grown in a very carefully redistilled water, prepared by redistilling the laboratory water in glass from potassium dichromate and sulphuric acid and from alkaline potassium permanganate, the product being condensed in a platinum tube. Only ferric hydrate was used in this case. The total transpirations were 40.6 grams for the redistilled water and 54.6 grams for the same with ferric hydrate.

These results with distilled water seem to make it very certain that the roots of seedling wheat plants do give off substances which are poisonous to themselves, and that these substances can be removed or corrected by carbon black or ferric hydrate.

Whether the toxic substances found in Takoma soil are of the same nature and of similar origin to those given off by wheat roots can not be decided at present, but it seems very probable that many soils will be found to contain toxic organic substances which have arisen from the growth of plants therein. This is interesting in connection with the fact that bog soils contain a water-soluble substance which is toxic to some algæ, as has been shown by one of the present authors.[a]

CONCLUSION.

Native and cultivated plants growing upon Takoma soil exhibit peculiar structures similar to those observed in case of a soil subject to drought. Wheat seedlings are much stunted even when the water content is kept practically constant throughout their growth. Therefore the property of the soil which is active in stunting wheat is something other than lack of water.

[a] Livingston, B. E., Physiological Properties of Bog Water. Bot. Gaz. 39: 348–355, 1905.

This soil can be improved to a great extent by the addition of fermented stable manure, green manure (consisting of the stems and leaves of cowpeas), sumac and oak leaves, tannic acid, pyrogallol, calcium carbonate, and ferric hydrate. The first three of these fertilizers may be effective in increasing the amount of water-soluble nutrient materials in the soil, but, as has been pointed out, the others can not be effective in this way. With the exception of nitrate of soda, ordinary fertilizers have no beneficial effect.

When wheat seedlings are grown in aqueous extracts of this soil they make the same kind of growth as in the soil itself. The stunting power of the extract can be corrected by the addition of extract of stable manure, pyrogallol, calcium carbonate, ferric hydrate, and carbon black. This fact alone demonstrates that the beneficial effect of these substances when used upon the soil itself is not due to an indirect increase of soluble nutrient materials through a readjustment in the soil, since all material in the soil extract is already dissolved.

What may be the manner in which stable manure, green manure, and leaves have this effect is very difficult to determine, on account of the extreme complexity of these materials. But since the same kind of effects can be obtained without either directly or indirectly increasing the content of the medium in soluble nutrient materials, it becomes highly probable that the effect of the manures and of leaves is not due to any change in the nutrient conditions. This probability is assured in case of the other beneficial substances used. The soil is greatly benefited, without any alteration of the nutrient conditions, by the use of practically insoluble bodies, such as ferric hydrate and carbon. The only possible explanation of this fact is on the assumption that the soil contains deleterious bodies, probably organic in their nature, which are effective in producing the dwarfing of wheat plants. The effect of the insoluble bodies may lie merely in absorbing these toxic substances. That of tannic acid, pyrogallol, and possibly also of calcium carbonate may be due to chemical reactions set up by these reagents which so alter the toxic substances as to make them noninjurious.

It may be regarded as very well established by evidence presented in this paper, that the Takoma soil contains some substance or substances toxic to wheat plants. It is also indicated that bodies are given off by the roots of growing wheat plants which are deleterious to the growth of these plants or to that of other plants of the same kind following them. This suggests that so-called "exhausted" soils are poisoned soils, and that crop rotation is beneficial in agriculture because it prevents the accumulation in the soil of the injurious excreta of any one form of plant life. The toxic sub-

stances are not volatile nor do they pass off with steam, but they are concentrated on boiling the soil extract. Even under these conditions, however, the amount of them which can be obtained by extraction is far too small for a satisfactory chemical study of them. They are probably organic in their nature. Although this soil is slightly acid, evidence is presented that the toxicity is not due to the acidity. Whether or not the toxic substances are themselves acid in their reaction can not yet be stated.

Of course it is not meant by the conclusions of this paper that such bodies as ferric hydrate and pyrogallol are recommended for use as agricultural fertilizers; they have been used merely as reagents in the investigation of the properties of this particular soil. The only fertilizers so far found to be of practical use on Takoma lawn soil are stable manure, green manure, and lime. By the use of these and of green sumac leaves and pyrogallol an excellent lawn has at length been obtained upon this soil.

SUMMARY.

In the present paper it has been shown that Takoma soil contains a water-soluble nonvolatile substance or substances, probably organic in their nature, which are toxic to wheat plants, causing a stunting of their growth. The toxicity of the soil is corrected by the use of stable manure, green manure, leaves of sumac, oak, etc., tannic acid, pyrogallol, calcium carbonate, ferric hydrate, and carbon black. Tannic acid and pyrogallol probably act chemically upon the toxic bodies, rendering them harmless, calcium carbonate may act chemically or as an absorbent, while ferric hydrate and carbon black probably act merely as absorbents.

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